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A Search for Single Top Quark Production at DØ

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FOR THE DØ COLLABORATION

Abstract

We present details of a search for electroweak production of single top quarks in the electron+jets and muon+jets decay channels. The measurements use ≈ 90 pb^{-1} of data from Run 1 of the Fermilab Tevatron collider, collected at 1.8 TeV with the DØ detector. We use events that include a tagging muon, implying the presence of a b jet, to set an upper limit at the 95% confidence level on the cross section for the s-channel process $p\bar{p} \rightarrow tb + X$ of 39 pb. The upper limit for the t-channel process $p\bar{p} \rightarrow tqb + X$ is 58 pb.

1 Introduction

The DØ collaboration has recently published the results of a search for single top quarks produced in association with a bottom quark or a light quark and a low-p_T b quark [1]. The CDF collaboration has reported similar measurements [2]. These analyses search for two independent modes that produce top quarks singly: the s-channel process $q'\bar{q}\rightarrow tb$ with a predicted cross section of $\sigma = 0.75 \pm 0.12$ pb [3]; and the t-channel process $q'g\rightarrow tqb$ with $\sigma = 1.47 \pm 0.22$ pb [4]. These values have been recently updated [3, 4]. Events are identified by the presence of one isolated electron or muon, and missing transverse momentum assumed to be from the decay of a W boson to a lepton and neutrino. The events must also contain two to four jets, with one or more having an associated muon to tag it as a possible b jet.

The published paper of the DØ results contains a complete summary of the analysis and details of the data and Monte Carlo event samples and electron and muon identification criteria. Efficient identification with a low fake rate is crucial to the success of the search. At the start of the analysis, the dominant background in the electron channel is from multijet events with a jet misidentified as an electron, and in the muon channel the main background is from events without a real muon from a W boson decay. An in-depth discussion of the backgrounds and of the efficiencies for trigger selection, particle identification, and cosmic ray rejection is available in a conference paper [5]. Here, we focus on the details of the event selections, and on the properties of the final candidate events.

We use the notation "tb" to refer to both $t\bar{b}$ and the charge-conjugate process $\bar{t}b$, and "tqb" for both $tq\bar{b}$ and $\bar{t}\bar{q}b$. The backgrounds referred to as $t\bar{t}$ and $Wb\bar{b}$ are self-explanatory. The $Wc\bar{c}$ background includes all contributions from $p\bar{p}\rightarrow W{+}c\bar{c}, W{+}c\bar{s}, W{+}\bar{c}s$, and $W{+}s\bar{s}$. The Wjj background includes events with only u, d, or g jets. The $Wb\bar{b}$, $Wc\bar{c}$, Wjj, WW, and WZ sets are Monte Carlo samples used to cross check the W+jets background, which is measured using data.

2 Baseline Event Selections

We apply a "baseline" set of event selections in order to choose all possible candidates after triggering. The electron channel and muon channel baseline samples are defined as those events which have at least one isolated lepton of the type expected and two or more jets. For data, the events must pass at least one of the Level 2 filters in the trigger and both of the Main Ring vetoes. Monte Carlo (MC) events must pass at least one filter. The baseline selections are given in Table 1. The effects of these extremely loose selections on the data and MC events are shown in Table 2.

The baseline samples for QCD are defined slightly differently to the others: the sample in the electron channel has at least three jets, not two, and no isolated electron is required; the sample in the muon channel has at least one nonisolated muon instead of the isolated one, as well as the two jets.

Invited plenary talk presented at the XVth International Workshop on High Energy Physics and Quantum Field Theory, Tver, Russia, 14th–20th September 2000.

Fewer muon channel events make it into the baseline samples than electron channel ones because of the large difference in overall lepton identification (ID) efficiencies. Of leptons that generate a trigger, we reconstruct and identify only $\sim$0.6$\times$ as many isolated muons as electrons.

Cut No.	Variable Definition	Variable Name	Cutoff	Main Backgrounds Rejected
Electron and Muon Channels				
1	Pass the triggers and filters (and vetoes for data)			QCD
2	Min. transverse energy of jet 1	E_T(jet1)	> 5 GeV	QCD, W+jets
3	Min. transverse energy of jet 2	E_T(jet2)	> 5 GeV	QCD, W+jets
4	Max. pseudorapidity of jet 1	$\|\eta^{\rm det}(\text{jet1})\|$	< 4.0	QCD
5	Max. pseudorapidity of jet 2	$\|\eta^{\rm det}(\text{jet2})\|$	< 4.0	QCD
Electron Channel Only				
6	PELC that passes electron ID			jets, photons
7	Min. transverse energy of electron	$E_T(e)$	> 20 GeV	QCD
8	Fiducial pseudorapidity of electron	$\|\eta^{\rm det}(e)\|$	$< 1.1, 1.5$–2.5	
Muon Channel Only				
9	PMUO that passes isolated muon ID			cosmics, patrec errors
10	Min. transverse momentum of muon	$p_T(\mu)$	> 20 GeV	QCD
11	Fiducial pseudorapidity of muon	$\|\eta^{\rm det}(\mu)\|$	< 1.7	
Tagging Muon				
12	PMUO that passes tagging muon ID			cosmics, patrec errors
13	Min. transverse momentum of muon	$p_T(\mu)$	> 4 GeV	QCD
14	Fiducial pseudorapidity of muon	$\|\eta^{\rm det}(\mu)\|$	< 1.7	

Table 1: The baseline event selection variables and cutoffs in the electron and muon channels. A PELC is an energy cluster in the calorimeter that has passed certain criteria in DØ's main event reconstruction package RECO. A PMUO is a muon candidate from RECO. "patrec" is short for "pattern recognition".

Event Type	Electron Channel % of Post-Trigger Sample Before μ-Tag	Electron Channel % of Post-Trigger Sample After μ-Tag	Muon Channel % of Post-Trigger Sample Before μ-Tag	Muon Channel % of Post-Trigger Sample After μ-Tag
Signals				
MC tb	59%	8.2%	24%	3.5%
MC tqb	62%	5.9%	27%	2.7%
Backgrounds				
MC $t\bar{t}$	71%	13.5%	28%	5.6%
MC $Wb\bar{b}$	50%	4.7%	24%	2.2%
MC $Wc\bar{c}$	55%	1.2%	29%	0.5%
MC Wjj	51%	0.1%	26%	0.1%
MC WW	62%	1.1%	20%	0.4%
MC WZ	61%	2.2%	20%	0.7%
QCD data	79%	0.4%	2.7%	0.1%
Signal data	1%	0.01%	0.3%	0.01%

Table 2: For the electron and muon channels, the percentage of post-trigger event samples which remain in the baseline samples before and after applying the requirement for a tagging muon.

3 Loose Event Selections

We apply a number of cleanup cuts to the baseline event samples in order to remove misreconstructed events and those that have final state objects in them which are not expected in the signals. These cuts and their effects are described here.

3.1 Loose Cuts for the Electron and Muon Channels

3.1.1 *Extra Leptons and Photons*

We reject events from the baseline samples which have more than one isolated lepton in them that passes the identification requirements. A muon can have high p_T (> 20 GeV) or low p_T ($4 < p_T \leq 20$ GeV). This cut is designed to remove Z, $t\bar{t}$, WW, and $WZ \rightarrow$ dileptons backgrounds. It also rejects some cosmic ray events in the muon channel. In addition, we remove events containing one or more photons. This is intended to reject $t\bar{t}\rightarrow ee$ and $Z\rightarrow ee$ events where one of the electrons has not had its track reconstructed (which happens for ∼10% of fiducial electrons), $W\gamma$+jets events, events where there is a bremsstrahlunged photon, and events where a jet fakes a photon.

Table 3 shows the percentage of events in the tagged baseline samples that fail each of these cuts either exclusively (i.e., they fail exactly one of these cuts and pass all other loose selections), or inclusively (i.e., they fail one of these cuts and any other of the loose set of cuts). These four cuts reject 13.6% (e-channel) and 8.7% (μ-channel) of the $t\bar{t}$ background events that are not removed by any other cuts, while rejecting less than 1% of the s-channel signal events and only 1.9–2.7% of the t-channel ones. Note that the WW and WZ MC samples do not include dilepton decays, otherwise the rejection rates could be higher than shown.

Effects of the Extra Object Rejection Cuts								
	Electron Channel				Muon Channel			
	Electron	High-$p_T\mu$	Low-$p_T\mu$	Photon	Electron	High-$p_T\mu$	Low-$p_T\mu$	Photon
				Fail Exclusively				
Signals								
MC tb	—	—	—	0.4	—	—	0.1	0.1
MC tqb	0.4	—	0.3	2.0	0.4	—	0.1	1.4
Backgrounds								
MC $t\bar{t}$	3.4	3.3	1.6	5.3	3.9	1.0	0.7	2.9
MC WW	—	—	—	4.2	—	—	—	—
MC WZ	—	—	—	1.4	0.6	—	—	1.2
QCD data	—	—	—	—	—	—	0.4	—
Signal data	—	—	—	—	—	—	—	—
				Fail Inclusively				
Signals								
MC tb	—	—	—	0.5	0.2	0.1	0.2	0.3
MC tqb	0.5	—	0.4	2.7	0.6	—	0.2	3.2
Backgrounds								
MC $t\bar{t}$	4.3	5.1	2.2	8.0	8.5	2.2	1.4	7.7
MC WW	—	—	—	5.6	—	—	—	—
MC WZ	0.7	0.3	—	1.4	2.4	—	0.6	4.2
QCD data	—	—	—	—	—	—	6.9	0.1
Signal data	—	—	—	—	—	—	1.8	—

Table 3: Percentages of the tagged baseline event sets which fail each of the extra lepton or photon vetoes exclusively or inclusively. The W+jets MC samples (not shown) are negligibly affected.

3.1.2 *Mismeasured Jets*

We check the quality of every jet in the data with $E_T > 5$ GeV and $|\eta^{\mathrm{det}}| < 4.0$. We do not apply these cuts to MC since the details of the jets are not modeled well enough and the sources of noise are not present. Instead, we correct for the small loss in efficiency. The quality checks are:

- Fraction of E_T in the electromagnetic calorimeter layers ($F(E_T^{\mathrm{EM}})$) < 0.9
- $-0.05 <$ Fraction of E_T in the coarse hadronic calorimeter layers ($F(E_T^{\mathrm{CH}})$) < 0.5
- Ratio of E_T's of hottest cell in jet to next-hottest cell (R_{Hotcell}) < 10

If any jet in an event fails any of these requirements, we call it a "bad jet" and discard the event, since the E_T of the jet cannot be relied upon. The fraction of E_T in the coarse hadronic calorimeter layers can go slightly negative because corrections for hot cells have been made in the reconstruction package before the cells are clustered into jets, and occasionally more energy has been subtracted from an individul cell's energy than was necessary. Table 4 shows the exclusive and inclusive percentages of tagged baseline events which fail these cuts.

Effects of the Jet Quality Cuts						
Event	Electron Channel			Muon Channel		
Type	$F(E_T^{\mathrm{EM}})$	$F(E_T^{\mathrm{CH}})$	R_{Hotcell}	$F(E_T^{\mathrm{EM}})$	$F(E_T^{\mathrm{CH}})$	R_{Hotcell}
			Fail Exclusively			
QCD data	0.7	0.4	0.1	0.2	0.5	—
Signal data	0.9	1.7	—	0.9	—	—
			Fail Inclusively			
QCD data	5.1	2.3	0.6	4.3	3.0	0.4
Signal data	2.6	2.6	—	2.7	2.7	0.9

Table 4: Percentage of the tagged baseline event samples which fail each jet quality requirement exclusively or inclusively.

3.1.3 *Jet E_T and $|\eta^{\mathrm{det}}|$ Cuts*

We now apply some cuts on the jets designed to keep as much signal acceptance as possible while rejecting some obvious backgrounds in the baseline samples. The requirements on the jets are:

- $E_T(\mathrm{jet1}) > 15$ GeV
- $E_T(\mathrm{jet2}) > 10$ GeV
- $|\eta^{\mathrm{det}}(\mathrm{jet1})| < 3.0$

After we have made these demands, we require:

- $2 \leq n_{\mathrm{jets}} \leq 4$

Table 5 shows the percentages of tagged baseline events which fail the minimum E_T, maximum $|\eta^{\mathrm{det}}|$, and multiplicity requirement, either exclusively (fail exactly one of these cuts and pass all other loose selections) or inclusively (fail one of these cuts plus any other of the loose cuts).

Effects of the Jet Kinematics Cuts								
	Electron Channel				Muon Channel			
	E_T^{min}	$\|\eta^{\mathrm{det}}_{\mathrm{max}}\|$	$n_{\mathrm{jets}}^{\mathrm{min}}$	$n_{\mathrm{jets}}^{\mathrm{max}}$	E_T^{min}	$\|\eta^{\mathrm{det}}_{\mathrm{max}}\|$	$n_{\mathrm{jets}}^{\mathrm{min}}$	$n_{\mathrm{jets}}^{\mathrm{max}}$
	Fail Exclusively							
Signals								
MC tb	0.6	—		—	0.3	—		—
MC tqb	2.3	0.2		0.3	1.2	0.2		0.1
Backgrounds								
MC $t\bar{t}$	4.4	0.1		21.8	3.7	0.1		14.5
MC $Wb\bar{b}$	0.4	—		—	—	—		—
MC $Wc\bar{c}$	—	—		—	—	—		—
MC Wjj	—	—		—	—	—		—
MC WW	4.9	—		7.6	5.6	—		1.1
MC WZ	4.8	0.3		3.4	3.6	—		0.6
QCD data	0.4	—		1.3	2.4	—		0.7
Signal data	1.7	—		0.9	6.4	—		0.9
	Fail Inclusively							
Signals								
MC tb	4.9	0.1	4.3	—	4.4	0.1	3.9	—
MC tqb	6.5	1.1	4.0	0.3	6.5	2.0	4.4	0.1
Backgrounds								
MC $t\bar{t}$	9.2	1.2	1.1	27.5	10.9	1.4	0.9	27.1
MC $Wb\bar{b}$	10.6	0.1	10.0	—	11.5	0.1	11.4	—
MC $Wc\bar{c}$	13.3	0.6	13.3	—	10.6	1.2	10.6	—
MC Wjj	23.3	—	23.3	—	31.6	3.6	31.6	—
MC WW	10.4	—	5.6	8.6	13.5	1.1	3.4	4.5
MC WZ	9.9	0.7	4.1	3.4	11.5	1.2	6.1	2.4
QCD data	15.4	2.2	2.1	6.6	20.7	2.3	5.0	4.0
Signal data	29.3	5.2	16.4	2.6	44.5	0.9	20.9	5.5

Table 5: Percentages of tagged baseline events which fail each of the jet requirements exclusively or inclusively. (Note that events cannot fail the $n_{\mathrm{jets}}^{\mathrm{min}}$ cut exclusively, since it forms part of the baseline requirements.)

3.1.4 *Missing Transverse Energy*

There is a neutrino in each of our signal events from the decay of the W boson from the top quark decay, with an average E_T at the parton level of ∼48 GeV. Therefore, we make the following requirements of our events:

- $\not\!\!E_T^{\rm cal} > 15$ GeV
- $\not\!\!E_T > 15$ GeV

$\not\!\!E_T^{\rm cal}$ is the vector transverse energy imbalance in the calorimeters before correcting for energy carried away by any muons in the event. $\not\!\!E_T$ is the missing transverse energy after making such corrections.

Events with less than 15 GeV of $\not\!\!E_T$ (or $\not\!\!E_T^{\rm cal}$) are usually QCD multijet events where there is a fake electron or fake isolated muon, and where the $\not\!\!E_T$ is a fluctuation from the decay of a b hadron into a muon and its associated neutrino, or where one or more objects in the event has been mismeasured, thus generating fake $\not\!\!E_T$.

The choice of $\not\!\!E_T$ threshold of 15 GeV is a balance between two competing issues. We could increase the signal acceptance without much increase in the background by lowering the cut to 10 GeV. However, this then leaves less data below the $\not\!\!E_T$ threshold with which to measure the probabilities for a jet to fake an electron and for a nonisolated muon to fake an isolated one, which leads to larger errors in the final result. In Run 2, a shortage of data will no longer be a problem (and the fake electron probability should be much smaller with the addition of a 2 T central solenoid magnet), and therefore a lower $\not\!\!E_T$ threshold may be advantageous.

The percentages of tagged baseline events which fail the requirements on $\not\!\!E_T^{\rm cal}$ and $\not\!\!E_T$ are shown in Table 6. It should be noted that not many electron channel events fail this cut exclusively because there is a special set of cuts ("mismeasured $\not\!\!E_T$", described next) that is highly correlated with the $\not\!\!E_T^{\rm cal}$ and $\not\!\!E_T$ cuts.

Effects of the Missing Transverse Energy Cuts

Event	Electron Channel		Muon Channel	
Type	Fail Exclusively	Fail Inclusively	Fail Exclusively	Fail Inclusively
Signals				
MC tb	0.2	5.1	3.8	8.8
MC tqb	0.2	5.6	2.7	7.2
Backgrounds				
MC $t\bar{t}$	—	5.9	1.5	7.6
MC $Wb\bar{b}$	0.1	8.0	5.3	14.0
MC $Wc\bar{c}$	—	5.2	5.3	13.5
MC Wjj	—	2.3	5.3	10.5
MC WW	—	4.9	4.5	9.0
MC WZ	—	6.5	1.8	9.7
QCD data	0.1	63.7	15.6	58.1
Signal data	—	63.8	2.7	25.5

Table 6: Percentages of tagged baseline events which fail the minimum $\not\!\!E_T^{\rm cal}$ and $\not\!\!E_T$ requirements exclusively or inclusively.

3.1.5 *Mismeasured Missing Transverse Energy*

Some of the objects in the events are somewhat mismeasured, which leads to fake missing transverse energy aligned with or back-to-back with the object. There are many events near the $\not\!\!E_T > 15$ GeV threshold where the $\not\!\!E_T$ is back-to-back with the electron or isolated muon. Events with mismeasured $\not\!\!E_T$ can also have it aligned or anti-aligned with a jet. We therefore implement triangular-shaped cuts in the $(\Delta\phi, \not\!\!E_T)$ plane to remove these events.

The cuts are defined as follows. We keep events if:

- $(20/\pi) \times \Delta\phi(e, \not\!\!E_T) - \not\!\!E_T < 0.0$
- $(20/\pi) \times \Delta\phi(\text{jet}i, \not\!\!E_T) - \not\!\!E_T < 0$, for i = 1,2,3,4 in the electron channel
- $(20/\pi) \times \Delta\phi(\text{jet}i, \not\!\!E_T) + \not\!\!E_T > 20$, for i = 1,2,3,4 in the electron channel
- $(240/\pi) \times \Delta\phi(\text{isol } \mu, \not\!\!E_T) - \not\!\!E_T < 190$

The effects of these cuts on data and MC signals and backgrounds are shown in Table 7. Many of the problems observed with the jets are for ones in the intercryostat regions ($-1.4 \leq \eta^{\text{det}} \leq -0.8$ and $0.8 \leq \eta^{\text{det}} \leq 1.4$). For electrons, most of them are probably jets misidentified as electrons, and as such, a different type of algorithm has been used to reconstruct the energy than is appropriate. The E_T found with the cell-clustering algorithm and with a jet-cone algorithm is not the same, and this can create a small amount of false missing transverse energy. It can be seen from the table that the cuts are quite powerful at rejecting QCD multijet background in the electron channel. In the muon channel, the cuts do not need to be very tight because the QCD $b\bar{b}$ background there is very small, and it is better to keep signal acceptance than reject more background in this case.

Effects of the Missing Transverse Energy "Triangle" Cuts				
Event	Electron Channel		Muon Channel	
Type	Fail Exclusively	Fail Inclusively	Fail Exclusively	Fail Inclusively
Signals				
MC tb	2.0	6.9	1.5	4.3
MC tqb	2.1	7.6	1.1	4.7
Backgrounds				
MC $t\bar{t}$	1.3	8.8	0.4	3.4
MC $Wb\bar{b}$	3.4	11.5	1.4	6.3
MC $Wc\bar{c}$	2.8	8.0	0.0	5.3
MC Wjj	2.3	4.7	5.3	5.3
MC WW	3.5	9.7	5.6	11.2
MC WZ	2.7	9.2	0.6	3.6
QCD data	9.7	80.3	1.5	24.1
Signal data	6.0	74.1	0.9	14.5

Table 7: Percentages of tagged baseline events which have an object aligned with or back-to-back to the $\not\!\!E_T$, and the $\not\!\!E_T$ is low, caused by a mismeasurement of the object's E_T.

3.1.6 *Mismeasured Tagging Muon Transverse Momentum*

To avoid problems with a neural network search (in progress), we remove events if the tagging muon p_T has been severely mismeasured. We keep tagged events if:

- $p_T(\text{tag } \mu) < 500$ GeV

Table 8 shows the percentage of tagged baseline events removed by this cut.

Effects of the Tagging Muon Maximum p_T Cut				
Event	Electron Channel		Muon Channel	
Type	Fail Exclusively	Fail Inclusively	Fail Exclusively	Fail Inclusively
Signals				
MC tb	0.2	0.2	0.2	0.3
MC tqb	0.1	0.1	0.2	0.2
Backgrounds				
MC $t\bar{t}$	0.1	0.3	—	0.2
MC $Wb\bar{b}$	—	—	—	—
MC $Wc\bar{c}$	0.3	0.3	—	—
MC Wjj	—	—	—	—
MC WW	—	—	—	—
MC WZ	—	—	—	0.6
QCD data	0.1	0.1	—	0.1
Signal data	0.9	0.9	—	—

Table 8: Percentages of tagged baseline events which have a badly mismeasured tagging muon.

3.2 Additional Loose Cuts for the Muon Channel

The muon channel needs several cleanup cuts which are not applicable to the electron channel because there are more problems with isolated muon reconstruction than with electrons, and because there are two muons in the final state for tagged events, which give rise to additional sources of background.

3.2.1 *Misreconstructed Isolated Muons*

When a muon has very high momentum, its track is not bent much in the toroid, and its p_T can be reconstructed to have an arbitrarily high value. This in itself is not a problem, or an indication that the reconstructed muon does not refer directly to a real high-p_T muon. However, when it occurs, fake missing transverse energy is generated in the event back-to-back with the muon. Since we use $\not\!\!E_T$ to characterize events and to separate signal from background, if it is corrupted, we can no longer be sure about the kinematics of the event and it is best to reject such events. Therefore, we keep events only if:

- $p_T(\text{isol}\mu) < 250$ GeV or $\not\!\!E_T < 250$ GeV

That is, we reject events where both p_T^μ and $\not\!\!E_T$ are high. There is no explicit demand that the muon and $\not\!\!E_T$ be back-to-back since almost every event which has high muon p_T and high $\not\!\!E_T$ has them back-to-back. They are also extremely correlated in magnitude, because almost all of the $\not\!\!E_T$ is being generated by the mismeasurement of the muon p_T. (There are a handful of events where the $\not\!\!E_T$ is extremely high and the muon is properly measured; they are also rejected by this cut.) The results are shown in Table 9. For tagging muons, we do not see this problem and therefore we do not need to apply a similar cut.

Effects of the Mismeasured Isolated Muon Cut		
Event Type	Fail Exclusively	Fail Inclusively
Signals		
MC tb	0.1	0.6
MC tqb	0.2	0.8
Backgrounds		
MC $t\bar{t}$	0.1	1.0
MC $Wb\bar{b}$	0.3	0.7
MC $Wc\bar{c}$	—	1.2
MC Wjj	—	—
MC WW	—	—
MC WZ	—	0.6
QCD data	0.1	2.5
Signal data	—	2.7

Table 9: Percentages of tagged baseline muon events which have a very high-p_T isolated muon and very high $\not\!\!E_T$. When this occurs, they are back-to-back and highly correlated in magnitude.

3.2.2 *Mismeasured Isolated Muon Transverse Momentum*

To avoid problems with a neural network search (in progress), we remove events if the isolated muon p_T has been severely mismeasured. We keep muon channel events if:

- $p_T(\mathrm{isol}\mu) < 500$ GeV

Table 10 shows the percentage of tagged baseline events removed by this cut. No events are removed solely because of it; it was applied as a precautionary measure to protect the neural network analysis.

Effects of the Isolated Muon Max p_T Cut	
Event Type	Fail Inclusively
Signals	
MC tb	0.4
MC tqb	0.5
Backgrounds	
MC $t\bar{t}$	0.5
MC $Wb\bar{b}$	0.1
MC $Wc\bar{c}$	0.6
MC Wjj	—
MC WW	—
MC WZ	0.6
QCD data	1.4
Signal data	2.7

Table 10: Percentages of tagged baseline events which have a badly mismeasured isolated muon. No events fail this cut and no other cuts.

3.2.3 *Cosmic Rays*

In the muon channel, there is a significant residual contamination from cosmic rays, even after all other loose selections have been applied. Figure 1 shows $\Delta\phi(\text{isol } \mu, \text{tag } \mu)$, the opening angle in the transverse plane between the isolated and tagging muons in the event. In the data, there is a large peak when the muons are back-to-back, indicative of cosmic ray contamination. There is no matching peak in the opening angle in η^{det} between the muons because the cosmic rays do not necessarily pass through the DØ detector at the same z position as the primary vertex. The pattern recognition algorithm tends to drop some of the muon chamber hits from the tracks and pull the tracks in the r-z plane so that both halves of the track appear to originate from the primary vertex. After track fitting, the tracks are no longer sufficiently back-to-back in η^{det} to cause a peak in the distribution. Since the peak in the $\Delta\phi$ distribution is sharp and cannot be gotten rid of with any sophisticated examination of the hits used on tracks, or muon p_T difference, for example (and we tried many things, since this cut has such a detrimental effect on signal acceptance), we simply apply a cut on the $\Delta\phi$ distribution to remove this background. It is important to reject these events from the analysis since they are not included in our background model, and consequently they significantly degrade the search sensitivity in the muon channel.

We keep events only if they have:

- $\Delta\phi(\text{isol}\mu, \text{tag}\mu) < 2.4$ radians

For the QCD background events, what is shown in Fig. 1 as isolated muons is actually nonisolated ones. The peak near zero for this data is therefore from double-tagged jets.

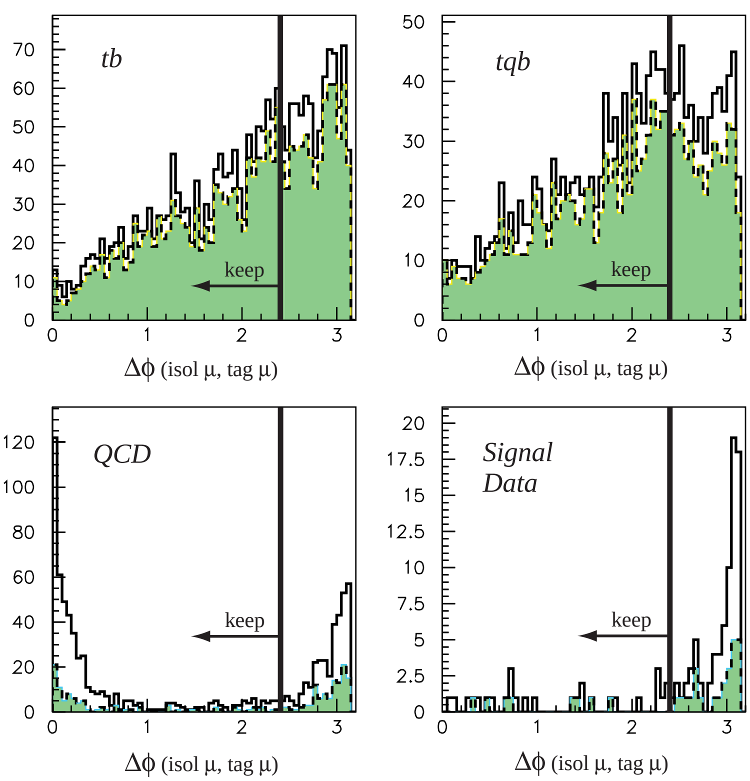

Figure 1: Distributions of the opening angle between the isolated and tagging muon. The open histograms show the tagged baseline samples,and the shaded histograms show the tagged loose set of events. Cosmic ray contamination is seen in the data, but not in Monte Carlo signal events.

We show the effects of the $\Delta\phi$ cut in Table 11.

Effects of the Cosmic Ray Cut		
Event Type	Fail Exclusively	Fail Inclusively
Signals		
MC tb	33.5	39.9
MC tqb	26.3	34.2
Backgrounds		
MC $t\bar{t}$	16.1	34.8
MC $Wb\bar{b}$	31.3	41.8
MC $Wc\bar{c}$	31.2	42.9
MC Wjj	26.3	42.1
MC WW	23.6	33.7
MC WZ	31.5	44.8
QCD data	13.2	39.5
Signal data	23.6	73.6

Table 11: Percentages of baseline tagged muon channel events which have the isolated muon and a tagging muon back-to-back in $\Delta\phi$.

3.3 Summary of the Loose Event Selections

Table 12 summarizes the loose cuts used in this analysis. These event selection requirements are applied to the baseline samples of events, and are designed to keep as much of the single top quark signals as possible while rejecting obvious nonsignal events, in preparation for the final tight set of cuts. The efficiencies of the loose selections are shown in Table 13.

After the baseline selections, there are 116 candidates in the electron channel and 110 in the muon channel. These are almost all QCD multijet events with a fake electron, or cosmic ray and fake isolated-muon events. After the loose event selections, there remain 21 candidates in the electron channel and 8 in the muon channel; still just over half are fake-lepton events. The percentage of these events which are expected to be from single top quark production (s-channel and t-channel combined) has improved from 0.53% in the electron channel after the baseline selections to 2.5% after the loose selections, and in the muon channel the percentage of signal has increased from 0.43% to 3.0%.

Loose Event Selections				
Cut No.	Variable Definition	Variable Name	Cutoff	Main Backgrounds Rejected
Electron and Muon Channels				
1	No extra electrons	n_e	$= 1$ or $= 0$	$t\bar{t}$, WZ, WW
2	No extra muons (low or high p_T)	$n_{\mathrm{isol}\mu}$	$= 0$ or $= 1$	$t\bar{t}$, cosmics, WZ, WW
3	No photons	n_γ	$= 0$	$t\bar{t}$, WZ, WW
4	No bad jets	$F(E_T^{\mathrm{EM}})$	< 0.9	Mismeasured events
		$F(E_T^{\mathrm{CH}})$	> -0.05, < 0.5	
		R_{Hotcell}	< 10	
5	Min. transverse energy of jet1	$E_T(\mathrm{jet1})$	> 15 GeV	W+jets, QCD
6	Min. transverse energy of jet2	$E_T(\mathrm{jet2})$	> 10 GeV	W+jets, QCD
7	Max. pseudorapidity of jet1	$\|\eta^{\mathrm{det}}(\mathrm{jet1})\|$	< 3.0	Wjj, QCD
8	Max. pseudorapidity of jet2	$\|\eta^{\mathrm{det}}(\mathrm{jet2})\|$	< 4.0	Wjj, QCD
9	Minimum number of jets	n_{jets}	≥ 2	W+jets, WW, WZ
10	Maximum number of jets	n_{jets}	≤ 4	$t\bar{t}$; QCD, WW, WZ
11	Min. missing transverse energy	$\not\!\!E_T^{\mathrm{cal}}$, $\not\!\!E_T$	> 15 GeV	QCD, W+jets
12	Mismeasured $\not\!\!E_T$ ("triangle cuts")			QCD
13	Mismeasured tagging muon	$p_T(\mathrm{tag}\ \mu)$	< 500 GeV	Mismeasured events
Muon Channel Only				
14	Mismeasured isolated muon	$p_T(\mathrm{isol}\ \mu)$, $\not\!\!E_T$	< 250 GeV	Mismeasured events
15	Mismeasured isolated muon	$p_T(\mathrm{isol}\ \mu)$	< 500 GeV	Mismeasured events
16	No back-to-back muons	$\Delta\phi(\mathrm{isol}\ \mu, \mathrm{tag}\ \mu)$	< 2.4 rad	Cosmic rays

Table 12: The loose event selection variables and cutoffs in the electron and muon channels.

Loose Selection Efficiencies		
Event Type	Electron Channel	Muon Channel
Signals		
MC tb	87%	50%
MC tqb	83%	53%
Backgrounds		
MC $t\bar{t}$	46%	28%
MC $Wb\bar{b}$	79%	42%
MC $Wc\bar{c}$	79%	41%
MC Wjj	72%	32%
MC WW	69%	44%
MC WZ	77%	41%
QCD data	10%	11%
Signal data	18%	7%

Table 13: Percentages of the tagged baseline event samples which remain after the loose selections.

4 Tight Event Selections

Table 14 shows the tight event selection variables and cutoffs. The variables have been chosen for highest sensitivity to separate signals from backgrounds, and the cutoffs are optimized by maximizing the significance of the signal significance. After the tight selections, there remain 12 candidates in the electron channel data, and 5 in the muon channel. The percentage of expected signal increases to 3.8% in the electron channel and 4.2% in the muon channel.

Tight Event Selections

Cut No.	Variable Name	Variable Definition	Cutoff	Main Background Rejected
Electron Channel				
1	$H_T^{\mathrm{j12}e\nu}$	$E_T(\mathrm{jet1}) + E_T(\mathrm{jet2}) + E_T(e) + \not{E}_T$	> 125 GeV	W+jets
2	$H_T^{\mathrm{j34}'}$	$E_T(\mathrm{jet3}) + 5 \times E_T(\mathrm{jet4})$	< 47 GeV	$t\bar{t}$
3	$H_T^{\mathrm{j1}(4\nu)}$	$E_T(\mathrm{jet1}) + 4 \times \not{E}_T$	> 155 GeV	QCD
Muon Channel				
1	H_T^{j1234}	$E_T(\mathrm{j1}) + E_T(\mathrm{j2}) + E_T(\mathrm{j3}) + E_T(\mathrm{j4})$	> 70 GeV	W+jets
2	$H_T^{\mathrm{j34}'}$	$E_T(\mathrm{jet3}) + 5 \times E_T(\mathrm{jet4})$	< 47 GeV	$t\bar{t}$

Table 14: The tight event selection variables and cutoffs in the electron and muon channels.

5 Properties of the Candidate Events

Table 15 shows averages of some properties of the electron channel data and MC events after the loose event selections. Values for the muon channel are similar. The averages have been calculated for events after all correction factors have been applied.

Average Properties of the Candidate Events

Event Type	No. of Jets	No. of μ-Tags	Electron E_T [GeV]	$\not{E}_T$ [GeV]	Jet1 E_T [GeV]	Jet2 E_T [GeV]	Jet3 E_T [GeV]	Tagμ1 p_T [GeV]	Tagμ1 Jet-ID	m_{top} $(e,\nu,j1)$ [GeV]	m_{top} $(e,\nu,j2)$ [GeV]
Signals											
MC tb	2.1	1.04	47	54	85	47	16	17	1.4	206	154
MC tqb	2.5	1.04	44	52	80	46	26	14	1.5	204	167
Backgrounds											
MC $t\bar{t}$	3.4	1.07	50	64	104	66	39	18	1.6	232	181
MC $Wb\bar{b}$	2.0	1.04	47	47	64	33	9	13	1.3	186	140
MC $Wc\bar{c}$	2.0	1.00	45	46	62	33	10	13	1.3	177	135
MC Wjj	2.0	1.00	45	46	64	31	—	6	1.2	170	157
MC WW	2.5	1.00	41	53	72	37	21	10	1.4	195	140
MC WZ	2.5	1.03	46	54	73	35	18	12	1.4	207	156
W+jets data	2.5	—	44	40	71	35	20	—	—	190	150
QCD data	3.7	1.01	19	25	68	44	15	16	1.4	192	167
Signal data	2.9	1.00	49	43	78	37	26	12	1.3	195	162

Table 15: Average values of some variables of the tagged electron channel events that pass the loose cuts.

The s-channel single top quark events have an average of 2.1 jets reconstructed, whereas the t-channel events have 2.5 jets, showing that the second b jet is often not reconstructed as it has quite low p_T (naively, one might expect an average of ∼3.1 jets). Diboson backgrounds have similar jet multiplicity to t-channel signals, and $t\bar{t}$ and QCD events have significantly more jets on average.

We are most likely to identify a second tagging muon in $t\bar{t}$ events (∼7% of the tagged $t\bar{t}$ events have two tagging muons), since there are always two central, energetic b jets. However, the rate of double tags in single top events, at ∼4% of the single tagged events, is still usefully higher than for other backgrounds.

The kinematic properties of single top quark events lie between those of the energetic $t\bar{t}$ background events, and the more numerous W+jets events. Thus, it is more difficult to separate single top signals from background than to identify $t\bar{t}$ events.

The Tagged Candidate Events – Part 1 – Main Properties

Event No.	Cut Set	Run No.	Event No.	No. of Jets	Tagged Jet No.	Event Zone	Tight Var.1 [GeV]	Tight Var.2 [GeV]	Tight Var.3 [GeV]	m_{top} $(l,\nu,j1)$ [GeV]	m_{top} $(l,\nu,j2)$ [GeV]
						Electron Channel					
1	**T**	**76339**	**11474**	**2**	**1**	**EC/CF1**	**199**	**0**	**254**	**209**	**156**
2	**T**	**76579**	**30349**	**2**	**1**	**CC/CF1**	**144**	**0**	**176**	**138**	**358**
3	**T**	**81336**	**3313**	**3**	**1**	**CC/CF2**	**223**	**9**	**407**	**228**	**161**
4	**T**	**83044**	**8929**	**2**	**1**	**CC/CF1**	**155**	**0**	**232**	**155**	**155**
5	**T**	**84225**	**12800**	**2**	**1**	**CC/CF1**	**149**	**0**	**168**	**139**	**138**
6	**T**	**84681**	**13015**	**3**	**1**	**CC/CF2**	**255**	**22**	**232**	**178**	**167**
7	**T**	**84998**	**15724**	**2**	**2**	**CC/CF1**	**226**	**0**	**398**	**210**	**119**
8	**T**	**85780**	**17023**	**3**	**1**	**CC/CF1**	**199**	**21**	**295**	**185**	**113**
9	**T**	**85781**	**10705**	**3**	**2**	**CC/CF1**	**194**	**31**	**295**	**196**	**127**
10	**T**	**87987**	**1228**	**3**	**1**	**CC/CF1**	**225**	**22**	**209**	**161**	**213**
11	**T**	**91981**	**29111**	**2**	**1**	**CC/CF1**	**282**	**0**	**243**	**248**	**171**
12	**T**	**93039**	**29631**	**3**	**1**	**EC/CF1**	**181**	**21**	**366**	**211**	**157**
13	L	63799	13414	3	2	CC/CF1	*111*	20	*145*	133	123
14	L	85437	31896	3	1	CC/CF1	*124*	6	*139*	120	111
15	L	87449	1860	4	1	EC/CF1	130	*50*	*139*	165	140
16	L	88610	9826	4	3	CC/CF1	191	*48*	322	205	169
17	L	89372	12467	4	3	CC/CF1	428	*187*	352	382	271
18	L	89546	9435	2	1	CC/CF1	*104*	0	*110*	122	127
19	L	89708	34735	3	1	CC/CF2	130	13	*128*	168	96
20	L	91206	13727	3	1	CC/CF2	449	*51*	458	363	133
21	L	92225	17428	4	1	CC/CF1	231	*241*	*146*	172	205
						Muon Channel					
1	**T**	**81693**	**11454**	**3**	**2**	**CF1/CF2**	**134**	**16**		**214**	**97**
2	**T**	**83077**	**9934**	**3**	**2/2**	**CF1/CF1**	**243**	**39**		**177**	**164**
3	**T**	**83078**	**15303**	**3**	**2**	**CF1/CF1**	**86**	**16**		**121**	**112**
4	**T**	**84695**	**29699**	**3**	**2**	**CF1/CF1**	**241**	**36**		**185**	**174**
5	**T**	**90572**	**46085**	**2**	**2**	**EF/CF1**	**207**	**0**		**304**	**253**
6	L	85735	22588	2	2	CF1/CF1	*58*	0		135	118
7	L	87882	17098	4	3	CF1/CF1	165	*103*		154	175
8	L	92238	29	2	1	EF/CF2	*69*	0		167	121

Table 16: Main properties of the tagged candidate events after the loose event selection cuts. Values in bold type are for events which also pass the tight cuts. Values in italics show where the loose cut-set events fail one or more of the tight cuts.

Tables 16 and 17 show the properties of the individual data candidates that pass the loose or tight event selections. The event zone abbreviations in Table 16 are defined as follows: CC = electron in central calorimeter ($|\eta^{\text{det}}| < 1.1$); EC = electron in an end calorimeter ($1.5 < |\eta^{\text{det}}| < 2.5$); CF1 = muon in central spectrometer ($|\eta^{\text{det}}| \leq 0.6$); CF2 = muon in central spectrometer ($|\eta^{\text{det}}| > 0.6$); EF = muon in end spectrometer ($|\eta^{\text{det}}| < 1.7$). The junction between the central and end regions of the muon spectrometer occurs between $0.8 < |\eta^{\text{det}}| < 1.2$, depending on ϕ.

The Tagged Candidate Events – Part 2 – Kinematics

Event No.	Lepton E_T [GeV]	Lepton η^{det}	$\not{E}_T$ [GeV]	Jet 1 E_T [GeV]	Jet 1 η^{det}	Jet 2 E_T [GeV]	Jet 2 η^{det}	Jet 3 E_T [GeV]	Jet 3 η^{det}	Tag μ p_T [GeV]
				Electron Channel						
1	**43**	−1.7	**41**	**88**	−0.0	**26**	1.0	—	—	**6**
2	**21**	−0.3	**31**	**52**	0.2	**40**	−2.6	—	—	**26**
3	**24**	1.0	**78**	**97**	0.5	**25**	2.0	**9**	−0.2	**5**
4	**33**	−0.3	**43**	**60**	0.5	**19**	−1.7	—	—	**6**
5	**63**	0.1	**33**	**37**	−0.6	**17**	−1.8	—	—	**8**
6	**61**	−0.9	**35**	**94**	−0.6	**65**	0.3	**22**	1.7	**21**
7	**26**	−0.7	**77**	**88**	−0.9	**35**	−0.3	—	—	**7**
8	**38**	−0.5	**52**	**87**	0.0	**22**	−0.6	**21**	−1.5	**9**
9	**22**	−0.0	**52**	**86**	0.7	**34**	0.2	**31**	−1.8	**6**
10	**66**	0.7	**35**	**68**	0.3	**55**	−1.3	**22**	0.4	**15**
11	**80**	−0.6	**34**	**107**	0.3	**61**	−0.4	—	—	**25**
12	**28**	−2.2	**79**	**49**	0.1	**24**	0.3	**21**	−0.9	**5**
13	20	−0.8	27	37	1.2	27	−0.5	20	0.1	12
14	41	0.8	26	35	−0.1	22	0.6	6	0.1	5
15	26	2.0	19	65	−0.2	21	−1.3	16	2.6	14
16	65	−0.9	72	33	1.0	21	−0.4	20	0.2	6
17	124	0.9	36	209	0.6	59	−1.1	52	0.4	17
18	35	−0.7	20	28	0.3	21	1.4	—	—	7
19	35	1.0	17	60	−0.9	18	−0.3	13	−3.2	14
20	91	−0.9	65	196	−0.8	97	−1.1	51	−0.1	35
21	83	0.6	20	67	−0.2	61	−0.9	57	−0.2	9
				Muon Channel						
1	**38**	0.1	**52**	**87**	1.5	**31**	0.7	**16**	0.6	**7**
2	**36**	0.7	**19**	**114**	−0.9	**90**	0.7	**39**	1.7	**8**
3	**27**	0.1	**20**	**43**	−0.6	**26**	−0.1	**16**	0.7	**5**
4	**47**	−0.1	**38**	**115**	−0.8	**89**	−0.5	**36**	1.0	**33**
5	**70**	−1.3	**83**	**132**	−0.6	**75**	0.0	—	—	**18**
6	24	0.3	69	33	0.7	25	−0.5	—	—	5
7	22	−0.1	16	73	1.1	49	−0.6	28	−0.1	6
8	21	1.3	51	51	−1.0	18	2.1	—	—	110

Table 17: Kinematic properties of the tagged candidate events after the loose event selections. Values in bold type are for events which also pass the tight cuts. Not shown are electron event 15's jet 4, which has $E_T = 7$ GeV and $\eta^{\text{det}} = 0.2$, electron event 16's jet 4, which has $E_T = 6$ GeV and $\eta^{\text{det}} = -3.3$, electron event 17's jet 4, which has $E_T = 27$ GeV and $\eta^{\text{det}} = 1.1$, and electron event 21's jet 4, which has $E_T = 37$ GeV and $\eta^{\text{det}} = -0.8$. Also not shown are muon event 2's second tagging muon (jet 2 is double-tagged), which has $p_T = 4$ GeV, and muon event 7's jet 4, which has $E_T = 15$ GeV, and $\eta^{\text{det}} = -2.9$.

6 Summary

This paper has presented details of the baseline and loose event selections used in DØ's search for single top quark production at the Tevatron collider. The baseline criteria are chosen to be ultra-loose, to keep maximal signal acceptance. The loose criteria are chosen to remove mismeasured events from the samples and to reject events which are obviously not signals. Application of these selections reduces the data sample from approximately one million events in each of the electron and muon channels to 21 e+jets/μ candidates and 8 μ+jets/μ candidates. The combined s-channel and t-channel signal acceptance is 2.6% in the electron channel before requiring a tagging muon to identify a b jet, and 0.22% after this requirement. In the muon channel, the combined acceptance is 1.8% before tagging and 0.11% after. These acceptances are percentages of the total single top quark cross section with no branching fractions included. Most of the acceptance is lost by the demand for a fiducial isolated lepton that passes strict particle identification criteria, part of the baseline selections. The jet E_T thresholds, $\not{E}_T$ threshold, and mismeasured $\not{E}_T$ cuts make up the rest of the inefficiency in the electron channel. In the muon channel, an additional significant loss occurs from the cut applied to reject cosmic ray contamination.

We have presented averages of various properties of the signal and background samples after the loose selections. This information can help to determine how best to separate the samples. We have also shown the detailed properties of the candidate events remaining in the data after the loose selections. There is one double-tagged candidate, a muon channel event with two tagging muons in the second-highest-E_T jet. A double-tagged jet is highly likely to be a b jet, thus making this event particularly interesting. The reconstructed invariant mass from the isolated muon, missing transverse energy (interpreted as a neutrino from a W boson decay) and either of the first two jets ($m_{l\nu j} = 177$ GeV with jet 1 and 164 GeV with jet 2) is quite close to the average Tevatron value of the top quark mass, 174.3 GeV. In Run 2, we hope to have a much larger sample of data, with far more efficient b jet tagging using a silicon vertex detector as well as lepton tagging, and thereby to observe many more such candidates.

References

[1] B. Abbott *et al.*, DØ Collaboration, *"Search for Electroweak Production of Single Top Quarks in $p\bar{p}$ Collisions"*, Phys. Rev. D **63**, 031101(R) (2001).

[2] P. Savard, "*Search for Single Top Production with CDF*", to appear in the proceedings of the Meeting of the Division of Particles and Fields of the American Physical Society, The Ohio State University, Columbus, OH, August 2000.

[3] M.C. Smith and S. Willenbrock,"*QCD and Yukawa Corrections to Single Top Quark Production via $q\bar{q}{\to}t\bar{b}$*", Phys. Rev. D **54**, 6696 (1996).

This calculation has been recently updated by Brian Harris to use CTEQ5M1 as the parton distribution function set (PDF) instead of CTEQ3M, for a top quark mass $m_t = 174.3$ GeV, the Tevatron average value. The PDF change increases the result by 2.5%. The quoted error includes contributions from the choice of scale and PDF, and from the 5.1 GeV error on m_t, which dominates.

[4] T. Stelzer, Z. Sullivan, and S. Willenbrock,"*Single Top Quark Production via W-Gluon Fusion at Next-to-Leading Order*", Phys. Rev. D **56**, 5919 (1997).

This calculation has been recently updated by Zack Sullivan to use CTEQ5M1 instead of CTEQ3M, for a top quark mass of 174.3 GeV. The new CTEQ PDF has a major bug fixed in the evolution equations that generate the b quark distributions (present in all previous CTEQ and MRS PDFs). The bug fix lowers the t-channel single top quark cross section by 15%. The quoted error includes contributions from the choice of scale and PDF, and from the error on m_t.

[5] A.P. Heinson, "*Search for Electroweak Production of Single Top Quarks at DØ*", to appear in the proceedings of the Meeting of the Division of Particles and Fields of the American Physical Society, The Ohio State University, Columbus, OH, August 2000.